THE TROPICAL OCEAN OBSERVING SYSTEM

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Abstract

This paper describes the Tropical Ocean Observing System for physical climate, which is a multi-national effort to provide data for climate research and forecasting. In situ components of the observing system include the tropical moored buoys (Tropical Atmosphere Ocean/Triangle Trans-Ocean Buoy Network (TAO/TRITON) in the Pacific, Prediction and Research Moored Array in the Tropical Atlantic (PIRATA), and Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) in the Indian Ocean), the Argo array of profiling floats, the Global Surface Drifter Program (GDP), the Expendable Bathythermograph (XBT) Network, the Global Sea Level Observing System (GLOSS), and the Repeat Hydrography Program. These in situ components have been designed to complement a constellation of Earth observing satellites for measurements of sea surface temperature (SST), sea surface salinity (SSS), sea level, and surface winds. Most of the data from these observing system components is available in real-time or near-real-time.

The phenomena of primary interest in the tropical oceans span intraseasonal to decadal and longer timescales, including:

- El Niño/Southern Oscillation and its decadal modulation in the Pacific
- The Atlantic Meridional Mode and Equatorial Atlantic Zonal Mode
- The Indian Ocean Dipole/Zonal Mode
- The mean seasonal cycle, including the Asian, African, Australian, and American monsoons
- The intraseasonal Madden-Julian Oscillation, which originates in the Indian Ocean but affects all three ocean basins
- Decadal variability related, for example, to the Pacific Decadal Oscillation and the North Atlantic Oscillation
- Trends that may be related to global warming

Sustained, systematic and comprehensive observations are necessary to advance knowledge of critical processes that govern climate dynamics originating in the tropics. Observations have demonstrated their value for evaluating ocean models, constraining ocean state estimation and assimilation products, and validating climate forecast models, which can be used for advanced warning of natural hazards, urban and agricultural planning, and for many other societal benefits. A global tropical perspective is required not only because of the range and complexity of tropical phenomena that affect the climate system, but also because of basin-to-basin interactions that affect the evolution of climatic fluctuations. This paper reviews tropical ocean measurement efforts in the past decade. We also highlight major scientific advances enabled by the Tropical Ocean Observing System over the past 10 years and discuss future plans for the observing system over the next decade.

Key words: observing system, tropical climate, international collaboration

1. INTRODUCTION

The tropics constitute a key region of the Earth's climate system. They experience the highest solar irradiance on the planet and export heat to higher latitudes through complex circulations in the ocean and atmosphere. Intense insolation in the tropics leads to the highest open ocean sea surface temperatures (SSTs), which in turn contribute to vigorous ocean-atmosphere interactions that affect regional patterns of precipitation on intraseasonal to decadal timescales. Atmospheric heating associated with these patterns of precipitation energize teleconnections to higher latitudes that affect climate worldwide. The tropics are also the spawning ground for hurricanes, typhoons, and cyclones whose statistics (intensity, frequency, and spatial distribution) are strongly influenced by intraseasonal-to-decadal timescale climate variations.

Beyond advancing knowledge of critical processes that govern climate dynamics, observations are also needed to develop, initialize, and validate climate forecast

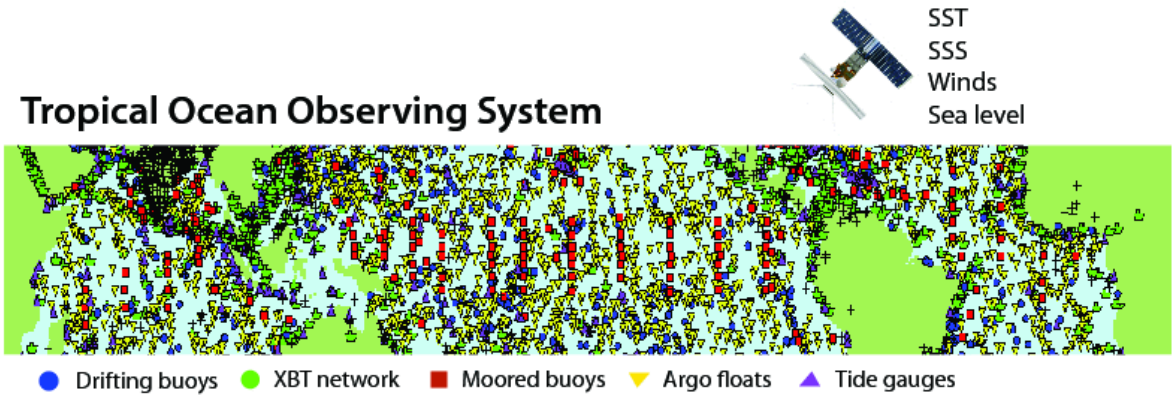

Figure 1. Elements of the Tropical Ocean Observing System. Shown are the positions of the platforms that transmitted data during the 30-day period ending July 15, 2012. Most XBT transects are therefore not shown. Also not shown are Repeat Hydrography lines. The geographic domain is global between 25ºS and 25ºN.

models on intraseasonal-to-decadal timescales. To address these observational needs, observing systems have been developed in all three tropical oceans, with most of the measurement systems providing data in real-time or near-real-time. This observing system is the legacy of major international research programs over the past 25 years, namely the Tropical Ocean Global Atmosphere (TOGA) Program [1], the World Ocean Circulation Experiment (WOCE) [2], and the Climate Variability and Predictability (CLIVAR) Program. This paper describes progress in implementing the Tropical Ocean Observing System for physical climate, the scientific advances it has enabled over the past decade, and future directions. There are complementary observing programs for ocean carbon, biogeochemistry, and ecosystems that are not covered here because of space limitations.

2. TROPICAL OCEAN OBSERVING SYSTEM

2.1. MOORED BUOYS

The Global Tropical Moored Buoy Array is built primarily around Autonomous Temperature Line Acquisition System (ATLAS) moorings designed by NOAA's Pacific Marine Environmental Laboratory (PMEL) and Triangle Trans Ocean Buoy Network (TRITON) moorings designed by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). These surface moorings have special attributes that make them a valuable technology for tropical climate studies. In particular, 1) they can be instrumented to measure both upper ocean and surface meteorological variables involved in ocean-atmosphere interactions, such as temperature, humidity, wind velocity, solar radiation, and longwave radiation; 2) they provide time series measurements at fine temporal resolution (minutes to hours) to resolve high-frequency oceanic and atmospheric fluctuations that would otherwise be aliased into the lower-frequency climate signals of primary interest; 3) they can be deployed and maintained on a fixed grid of stations so that measurements do not convolve variability in time and space. Ships dedicated to servicing the moored buoy arrays typically repeat at intervals of six months to one year. These cruises routinely collect standard shipboard data that accumulate as a valuable addition to the climate data base. Measurements include Conductivity-Temperature-Depth (CTD) station data and underway Acoustic Doppler Profiler (ADCP), thermosalinograph, CO_2 , and surface meteorological data

The TAO/TRITON array has been recording data since 1985 [3]. Measurements from PIRATA started in 1997 [4], and RAMA was initiated in 2004 [5]. The moorings are a contribution to OceanSITES [6], a global system of long-term, deepwater reference stations. See [7] for more details of the tropical moored buoy array.

2.2 ARGO

Argo is an international program to maintain a global, nominally 3x3-deg array of free-drifting profiling floats. Every 10 days each float reports temperature and salinity of the upper 2000 m of the ocean as well as the transit velocity at its parking depth. The data are made publicly available within hours of collection. Argo deployments began in 2000, and by November 2007 the array reached its initial target of 3000 active floats. Continued float deployments are required to maintain the array at design strength. The near-global coverage of Argo, combined with higher vertical resolution of temperature and salinity profiles from Argo floats

compared to moored buoys, make Argo a unique and valuable component of the Tropical Ocean Observing System.

2.3 DRIFTING BUOYS

The Global Drifter Program (GDP) is a branch of NOAA's Global Ocean Observing System (GOOS). Its objectives are to maintain a global 5x5-deg. array of 1250 ARGOS-tracked surface drifting buoys to meet the need for an accurate and globally dense set of in-situ observations of mixed layer currents, SST, atmospheric pressure, winds and salinity. The GDP began in 1988 and reached its initial target of 1250 global drifters in 2006. Continued drifter deployments are needed to maintain the array at this level. These data support short-term (seasonal to interannual) climate predictions as well as climate research and monitoring. Measurements of SST from drifting buoys are an important source of quality-control for satellite SST and SSS retrievals. More details of the GDP are given in Lumpkin et al. (in this volume).

2.4 XBT NETWORK

The Ship of Opportunity Program (SOOP) operates a global network of XBT systems onboard merchant ships. The data are transmitted in real-time and made available to the oceanographic and meteorological communities for operational (e.g., assimilation in ocean models) and scientific purposes. Temperature measurements from XBTs are available in the upper 800 m of the ocean at a vertical resolution of ~1 m. The repeat-sampling strategy makes these data valuable for quantifying long-term changes in ocean circulation and its redistribution of heat. Many of the transects have been operational since the 1990's, giving seasonally-resolved time series for over two decades. A unique aspect of the XBT program is its ability to measure temperature profiles in close proximity to land, something which is difficult to achieve with Argo. More details of the XBT network are given in Goni et al. (in this volume).

2.5 REPEAT HYDROGRAPHY

The U.S Global Ocean Carbon and Repeat Hydrography Program carries out a systematic and global re-occupation of 16 hydrographic sections to quantify changes in storage and transport of heat, fresh water, carbon dioxide (CO_2), and related parameters. Each section is repeated every ten years on average. The measurements span the entire depth of the water column with an along-track horizontal resolution of ~0.5-deg. Full-depth coverage and repeat sampling make these data a unique and valuable resource for identifying decadal variability and anthropogenic-induced changes in ocean circulation and physical and chemical properties.

2.6 TIDE GAUGES

Near real-time measurements of sea level from tide gauges are distributed by the Global Sea Level Observing System (GLOSS) data assembly center operated at the University of Hawaii, and historical data are archived and distributed by the NOAA National Oceanographic Data Center. Tide gauges are necessary for accurately measuring long-term trends in sea level and for calibration and validation of the measurements from satellite altimeters, which are assimilated into global climate models. See [8] for more details of GLOSS.

2.7 SATELLITE PRODUCTS

Satellites provide routine measurements such as sea surface temperature (SST), salinity (SSS), sea level, and surface winds with near-uniform sampling over the global tropics. The sampling allows for the estimation of higher order essential climate variables, such as wind stress curl, surface ocean currents, and the spatial gradients of SST and SSS, which are important for climate research but are difficult to derive from in situ measurements. The lifetime of a typical satellite sensor is several years, and the satellites generally repeat their orbits in one to ten days, laying the foundation for continuous records of essential climate variables. International collaboration and careful cross-platform calibrations have allowed some satellite data records to be extended for 2-3 decades [9]. The surface measurements provided by satellites complement the in situ observing systems described earlier.

3. SCIENTIFIC PROGRESS

In the past decade, the Tropical Ocean Observing System has enabled significant advances in our understanding of tropical climate. The observations from this system are also used routinely to improve ocean and climate models, to constrain ocean state estimation products, and to improve the initialization of climate predictions [10, 11, 12]. The highlights presented in this section briefly summarize some of these advances while emphasizing the high degree of complementarity of the individual elements of the Tropical Ocean Observing System.

3.1. TROPICAL PACIFIC OCEAN

Recent scientific highlights include observational verification of the "Recharge Oscillator" theory for ENSO, which provided a formal mathematical framework for the hypothesis that a build-up of excess

warm water in the equatorial band is a necessary precondition for the development of El Niño events [13]. El Niños of the 21st century have been characterized by SST anomalies along the equator that are largest near the international date line [14]. These events have been termed “date line” [15] or “modoki” [16] El Niños. This class of El Niños has different climate impacts than those with largest anomalies in the eastern Pacific [16]. What factors ultimately select for development of El Niños with largest SST anomalies in the eastern vs. central Pacific, though, are not known.

Sea level measurements from tide gauges and satellites consistently show strong positive trends in the western tropical Pacific since the early 1990s [17]. The trends are consistent with strengthening of the tropical Pacific trade winds and an acceleration of the global hydrological cycle over the past two decades. Partitioning the sea level trends into a climate change signal and natural variability is an ongoing challenge [17, 18], and it is unknown how the changes in sea level and ocean heat content feed back to affect ENSO and large-scale atmospheric circulation cells.

TAO/TRITON and Argo data are routinely used in ocean state estimation [10], operational ocean analyses [11], operational atmospheric analyses and reanalyses, and ENSO forecasting [12]. TAO/TRITON data have also been used extensively for model validation [19] and for satellite validation of surface winds [20], SST [21], rainfall [22], and shortwave radiation [23. Argo current data are also allowing detailed study of richly structured mid-depth (~1000-1500 m) velocity fields, which potentially play important roles in zonal heat and freshwater transport and vertical mixing [24].

3.2. TROPICAL ATLANTIC OCEAN

Significant scientific progress in the tropical Atlantic has been enabled by the Tropical Ocean Observing System in the past 10 years [4]. Advances include a definition of the factors responsible for the mean seasonal cycles of SST and SSS [25, 26, 27]. Studies have benefited from accurate surface heat and moisture fluxes estimated from high temporal resolution PIRATA mooring data. In the SST balance, latent heat flux and shortwave radiation are important at all latitudes, though within a few degrees of the equator oceanic processes involving advection and vertical mixing become prominent. Variations north of the equator are strongly influenced by meridional seasonal migrations of the ITCZ, which are associated with large wind, latent heat, shortwave radiation, and precipitation changes.

PIRATA, Argo, and satellite data were recently analyzed to show that mixed layer dynamics play an important role in interannual variability of the Atlantic Meridional Mode [28]. It has also been found that thick barrier layers in the tropical North Atlantic play a significant role in insulating the surface layer from turbulent mixing with the thermocline [29]. PIRATA data have been valuable for defining Equatorial Undercurrent (EUC) transports [30], and for validating model simulations [31]. PIRATA, surface drifting buoys, and XBT data have been valuable for defining seasonal to interannual variations of the Atlantic North Equatorial Countercurrent (NECC) and their relationships to tropical Atlantic modes of variability [32]. High-density XBT transects and satellite altimetry have recently been used to quantify seasonal to interannual variability of surface and subsurface zonal currents in the tropical Atlantic [33]. As with TAO/TRITON, PIRATA data are used routinely in ocean state estimation, operational oceanic and atmospheric analyses, and atmospheric reanalyses [4].

Velocity data from Argo floats have revealed alternating zonal jets in the mid-depth equatorial Atlantic Ocean [34]. The jets radiate energy upward on a timescale of 4-5 years, modulating the strength of surface currents and affecting coupled ocean-atmosphere variability in the equatorial Atlantic [35].

3.3. TROPICAL INDIAN OCEAN

Though some elements of the observing system in the Indian Ocean have been established only in the past several years, significant progress is beginning to be made. RAMA data indicate that subsurface temperature variations lead those at the surface by a season near the equator in the eastern basin, suggesting that anomalies in upper-ocean heat content may be a source of predictability for the Indian Ocean Dipole/Zonal Mode (IOD) as in the Pacific for ENSO [36]. In addition, zonal advection and surface heat fluxes are important in generating IOD SST anomalies [37].

In the Seychelles Chagos Thermocline Ridge (SCTR) region, pronounced intraseasonal heat fluxes associated with the MJO lead to large SST cooling events, especially in boreal winter. Data from a RAMA mooring and Argo floats captured two MJO events that resulted in strong intraseasonal SST variations (1.5 to 2°C in 20 days). At the mooring site, atmospheric fluxes dominated the upper ocean heat balance at the MJO timescale [38]. Data from RAMA, Argo, and satellites were used to show that on seasonal timescales, variability of SST in the SCTR is driven by a combination of the net surface heat flux, horizontal heat advection, and entrainment [39].

RAMA, Argo, and satellite data were also used to observe the oceanic response to cyclone Nargis, which made landfall in Myanmar on 2 May 2008 and was the

deadliest natural disaster to affect the Indian Ocean region since the 26 December 2004 tsunami. Intense ocean mixing and significant turbulent heat loss from the ocean surface (~600 W m^{-2}) occurred as Nargis passed near a RAMA buoy at 15°N, 90°E in the Bay of Bengal [40].

4. THE WAY FORWARD FOR THE NEXT TEN YEARS

During the next decade and beyond, climate observations must be managed within the context of an end-to-end system that includes data collection, modelling and assimilation, forecasting, and the provision of climate information and services to society for practical applications. Climate observing systems also need to evolve continually as we learn more about climate variability and change and as advances in data assimilation and climate forecast models impose new demands on the observing system. Research plays a critical role in guiding the evolution of observing systems by establishing scientific priorities, by developing new measurement technologies to address those priorities, and by performing high level quality control through scientific analyses of the data. Thus, as both stakeholder and partner, the research community needs to be an active participant in the governance structure of climate observing systems in order to ensure they are cost-effectively operated, preserve data continuity and quality, are responsive to evolving measurement requirements, and adhere to climate observing system principles [41].

In the foregoing sections we have illustrated the value of the Tropical Ocean Observing System for climate forecasting and research and highlighted the unique niche they fill in the Global Ocean Observing System. Based on these considerations, we believe that the Tropical Ocean Observing System forms an essential component of the ocean observing system for climate and that it is important to consolidate and build on advances made in the past decade. In particular, we recommend the following priority actions for the coming decade:

- Complete RAMA and reoccupy the discontinued PIRATA Southeast Extension site; sustain TAO/TRITON, PIRATA, and RAMA for climate forecasting and research on seasonal, decadal, and longer timescales.
- Continue deployment of Argo floats to maintain the full array for climate research and model initialization and validation. In addition, increase profile vertical resolution to 2 dbar, deploy floats with capability to sample the upper 1 m for validation of satellite SST and SSS, and deploy full-depth profiling floats, all of which will improve Argo tropical efficacy.
- Sustain the surface drifting buoy array for advancing knowledge of the role of ocean circulation in climate and for calibration of satellite SST and SSS data.
- Continue XBT Network and Repeat Hydrography to support research on intraseasonal-decadal variability and anthropogenic-induced trends of upper-ocean (0-800 m) and full-depth heat content, circulation, and heat transport, and for calibration of Argo.
- Maintain tide gauges for assessing sea level response to climate change and for calibrating satellite observations of sea level.
- Maintain continuity of satellite observations of SST, SSS, sea level, and surface winds for studying teleconnections between the tropical basins and the role of the global tropics in climate variability and change, and for climate forecasting and assessments.

Despite the growth and success of in-situ observing networks in the Pacific, Indian, and Atlantic Oceans in the past decade, gaps in the observing system remain. In particular, observations of the oceanic linkage between the tropical Pacific and Indian oceans, the Indonesian throughflow (ITF), have been limited. The ITF is believed to play significant roles in global ocean circulation and Indo-Pacific climate variability [42, 43]. The International Nusantara Stratification and Transport (INSTANT) program [44] provided comprehensive, simultaneous measurements in various inflow and outflow passages of the ITF, but only for a three-year period (2004-2006). Sustained observations of the ITF are important for understanding Indo-Pacific climate variability on a wide range of timescales, but remain a challenge.

The Argo and Drifting Buoy programs, as well as biogeochemical programs and numerous shorter-duration projects, rely on tropical moored buoy servicing cruises for deploying floats and obtaining other climate-relevant measurements. It is therefore crucial to maintain current semi-annual to annual cruises to service the tropical moored buoy array. More broadly, sustaining and enhancing the Tropical Ocean Observing System is a high priority because of its unique and essential role in support of climate forecasting and research.

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